Effects of Cryogenic Cooling on the Surface Quality and Tool Wear in End-Milling 6061-T6 Aluminium

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Abstract

The vast majority of machining operations use some type of cutting lubrication to facilitate improved machinability, which also constitutes reductions in surface roughness and increases in tool life. This occurs as a function of reducing the temperature at the cutting interface or zone and by providing a fluidised cushion between the cutter and the cutting interface. This also aids in improving chip formation and chip morphology. However, the major drawback of using conventional coolant is the increased environmental impact of coolant recycling. Other methods have been recently investigated and include chilled air and cryogenic methods. This paper provides one of the first attempts at using cryogenic coolant and lubrication methods for CNC milling of T6 aluminium using carbide tooling. The results suggest that using cryogenic methods provides a realistic alternative to conventional coolants for milling applications that is not only more environmentally friendly, but also reduces the surface roughness, provides better chip formation and increases tool life.

1. Introduction

Due to the increasing costs and the introduction of more restricted environmental regulations [1], using conventional cutting fluids is neither economical nor environmentally friendly anymore. Dry cutting however has failed to satisfy manufacturers and machinists in some cases due to low productivity, poor surface quality and short tool life. As a result, unconventional cooling methods such as minimum quantity lubricant (MQL) [2, 3], chilled air [4] and cryogenic machining have been introduced as an alternative methods to reduce or eliminate the use of cutting fluids whilst increasing machinability as compared to dry cutting condition.

Using liquid nitrogen as a cutting fluid has been defined as an environmentally friendly technique which also has the potential to improve the machinability as compared to conventional dry and wet machining [5]. Cryogenic machining consists of applying a liquefied gas, usually liquid nitrogen, to the cutting zone in order to reduce the cutting temperature, increase the cutting tool hardness, alter the friction and sometimes change the workpiece material behaviour at the cutting zone. This paper presents the empirical procedure used to investigate the effects of cryogenic cooling on the machinability of 6061-T6 aluminium alloy for slot milling operations. In addition, the obtained results from cryogenic machining are compared with that of traditional dry and wet machining in order to illustrate the effects of cryogenic cooling on the machinability of 6061-T6 aluminium.

2. Background

Different types of cutting fluids have been used for decades in order to improve the machinability of different materials in conventional cutting operations such as turning, milling and grinding. Using conventional cutting fluids is considered to be an effective method to alter the friction and reduce the temperature at the cutting zone, increase tool life and improve surface quality of machined parts. However, the costs of using conventional cutting fluids is not limited to the purchase and preparation, but also consists of maintenance and disposal costs [6]. Expanding governmental regulations and environmental concerns have increased the costs associated with the use of cutting fluids in machining operations [1]. It has been declared that the disposal expenses of the conventional cutting fluids could be as high as four times the initial purchase cost [6]. The costs associated with cutting fluids could form 16% to 30% of the total manufacturing costs, which is much higher than the 2%-4% tooling expense [7-9]. Klocke and Eisenblatter [9]

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declared that most companies have underestimated the costs associated with the cutting fluids including the health concerns, fluids maintenance, recycling and disposal costs and the costs of draining and cleaning of the machined parts and machining swarf.

Dry machining is introduced as the best method to eliminate the use of conventional cutting fluids in material cutting [9]. While higher cutting temperature in dry machining could soften the workpiece material and reduce the cutting forces, in some cases it exacerbates the cutting condition by producing lower surface quality and shorter tool life [10]. This is due to the increased chemical reactivity and welding tendency of the materials at elavated temperatures. For instance, in machining aluminium alloys the cutting temperature could exceed the melting point of the workpiece material resulting in the formation of built of edges on the cutting tool, smearing and re-depositing of the chips onto the machined surfaces, thus reducing surface quality [9].

Liquefied gases such as nitrogen, helium and carbon dioxide have attracted researchers for several years as an alternative cooling media to replace the conventional oil-based cutting fluid in cutting operations. In particular, liquid nitrogen is an odourless fluid which is lighter than air and evaporates at 77°K. In cutting operations, it could absorb the heat generated at the cutting zone and disperse into the surrounding atmosphere. Nitrogen is an inert gas, which forms more than 78% of the Earth's atmosphere. As a result, liquid nitrogen has the potential to be used as an environmentally friendly alternative to conventional cutting fluids.

In turning Ti-Al6-V4, Venugopal *et al.* [11, 12] declared that cryogenic cooling reduced the tool wear by 77% and 66% which resulted in a 240% and 71% increase in the tool life in comparison with dry and emulsion machining respectively. This has also been supported by experiments conducted by Bermingham *et al.* [13] where an increase in up to 58% in the tool life has been reported. This has been attributed to the reduction of the chemical affinity between the tool and workpiece materials due to the lower cutting temperatures associated with cryogenic machining. Hong [14] stated that cryogenic cooling could effectively improve the tool life, surface roughness and chip breakability of AISI 1008 low carbon steel by reducing the cutting temperature and ductility of the workpiece material. Dhananchezian *et al.* [15] reported that spraying liquid nitrogen into the cutting zone in machining 6061-T6 aluminium alloy reduced the stickiness of the material and cutting temperature up to 40%. As a result, a maximum increase of 40% in the shear angle has been achieved in comparison with dry machining. On the other hand, lower temperatures resulted in higher material hardness and thus 10% higher cutting forces as compared to dry machining. Biermann and Heilmann [16] studied the effect of cryogenic cooling using liquid/solid carbon dioxide on the burr formation in face milling 6082 aluminium alloy. They noticed that the quality of the machined surface is highly dependent on the cooling process. As a result, Biermann and Heilmann [16] reported that using carbon dioxide snow effectively reduced the burr formation as compared to dry machining.

3. EXPERIMENTS

Based on the literature, cryogenic cooling has been acknowledged for several years as an effective method to improve the machinability of some materials. For this research the effect of cryogenic cooling using liquid nitrogen on the surface roughness, chip morphology and tool wear mechanism when compared with traditional methods namely dry and water miscible coolants is investigated. The proposed machine tool for carrying out the experiments was a compact Bridgeport vertical CNC milling centre equipped with an 840D Siemens controller. The liquid nitrogen was delivered through a specially designed nozzle, in order to inject the cryogen into the tool-workpiece interface. A schematic setup of the cooling system is provided in figure 1.

Machining slot features is considered to be one of the most difficult operations in CNC milling due to the full engagement of the cutting tool with the workpiece material. In addition, as both sides of the cutting tool are enclosed with the slot walls it is difficult for the coolant to precisely penetrate into the cutting zone. Due to these difficulties, slot milling was proposed as the desired machining operation to be studied in this research. The cutting parameters selected for this study were derived from the cutting tool provider recommendations and are shown in table 1.

As shown in the table 1, the experiments were limited to two different feed rates and three cutting environments. A series of slots were machined using a 12mm multi-layer Ti1005 coated tungsten carbide slot drill out of 6061-T6 aluminum blocks under three cutting environments, namely dry, wet and cryogenic. All machining experiments were conducted in the CNC laboratory at the University of Bath. The cutting chips of each experiment were collected to be further studied under a scanning electron microscope (SEM). In addition, a Proscan 2000 optical profilometer was employed to measure the surface roughness of the machined samples.

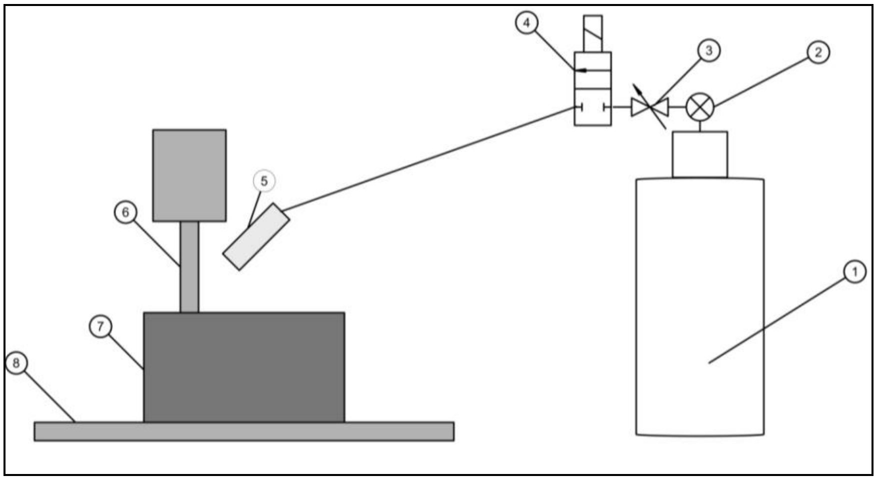

Figure 1 : Schematic setup for cryogenic machining, 1-Liquid nitrogen Dewar, 2- pressure gauge, 3- gate valve, 4- solenoid on/off valve, 5- specially designed nozzle, 6- cutting tool, 7- workpiece, 8- machine table

4. RESULTS

Unlike turning and drilling, in milling chip breakability is not a major concern as milling is an intermittent cutting operation, which inherently cannot produce continuous chips. Interestingly it should be noted that despite the authors' expectations the longest chips were made under the cryogenic cooling condition while the most uniform chips were produced using conventional coolant. This was expected as the chatter of the cutting tool under cryogenic environment was distinctively higher than that of dry and wet conditions. This could be explained by the non-uniform cooling effect of liquid nitrogen through the workpiece material and the reduction in ductility of the material.

SEM microscopic evaluation of the machining chips revealed that the surface quality of the chips produced under cryogenic condition was much higher than that observed from dry and wet conditions. In addition, as it is shown in figure 2 cryogenic cooling has resulted in the most uniform chip edge.

Table 1 : Specifications of Experiments

Experiment	Environment	Cutting Speed (rpm)	Feed Rate (mm/min)	Depth of Cut (mm)
1	Dry	5000	90	3
2	Wet	5000	90	3
3	Cryogenic	5000	90	3
4	Dry	5000	150	3
5	Wet	5000	150	3
6	Cryogenic	5000	150	3

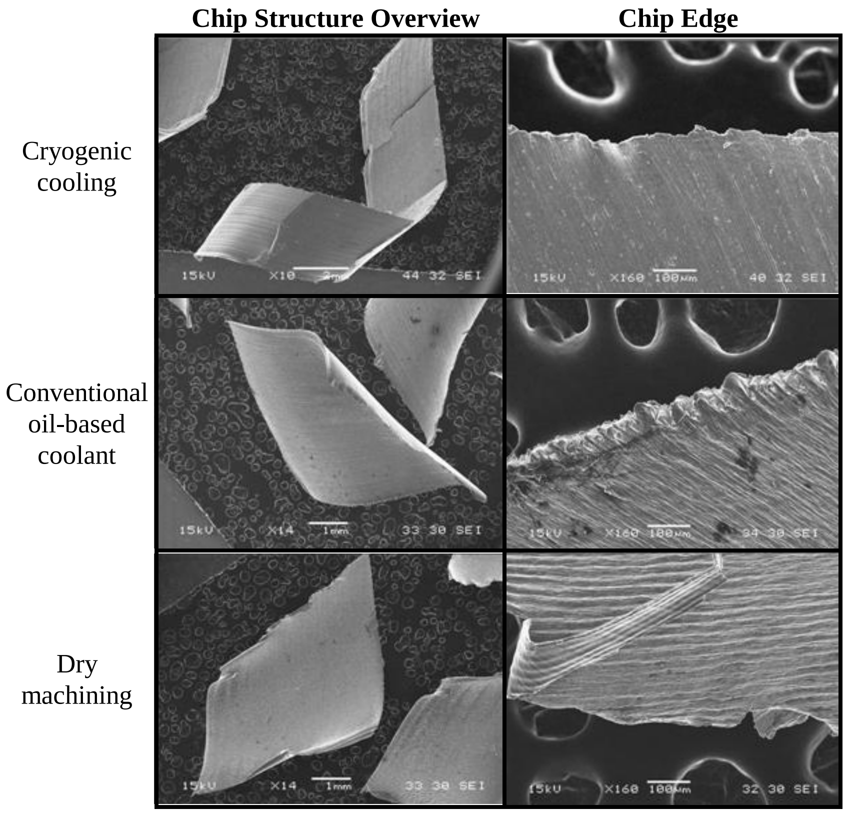

Figure 2 : SEM pictures of machined chips produced under a) Cryogenic; b) Wet; c) Dry environments (S= 5000rpm, f= 90mm/min)

In order to compensate the effect of tool wear on the surface finish, the study of the surface finish was limited to the beginning of each machined slot.. Even though a small surface sample was measured, the results discussed below clearly indicate differences between the differing cutting conditions.

The measured arithmetical mean deviation (Ra) surface roughness of the specimen is provided in figure 3. From figure 3 it is clear that the introduction of liquid nitrogen as a cryogenic coolant has resulted in a significant reduction in the surface roughness regardless of feed rate. Using cryogenic coolant at the cutting speed of 5000rpm and feed rate of 150mm/min resulted in more than a 43% reduction in the surface roughness as compared to dry machining. The highest surface roughness irrespective of feed rate was achieved when machining using conventional water miscible coolants. By applying conventional oil-based coolants into the cutting zone the surface roughness increased by up to 14% in comparison with dry machining.

As previously mentioned smearing and chip re-deposition is one of the major problems in dry machining of aluminium alloy. As illustrated in figure 4, due to the lack of space for effective chip removal and high cutting temperature, the machined chips were re-welded to the slot walls during the machining operation. This has resulted in poor surface quality of the walls and could affect the service life of the machined parts. In contrast, cryogenic cooling has effectively eliminated the chip re-deposition and improved the walls surface quality. A comparative illustration of the machined walls is provided in figure 4.

Due to the limited number of experiments and also because none of the cutting tools reached their maximum tool life, no quantitative evaluation could be performed, for examining the effect of cryogenic cooling on tool life in comparison with dry and wet environments. Microscopic investigations showed the presence of built up edges on the cutting tool in dry machining. The formation of built up edges is an inherent characteristic of machining aluminium due to its welding tendency and low melting point. Flow of the chips over the welded area has torn the built up edge form the cutting tool resulting in notching on the cutting edge as shown in figure 5. Excessive cooling effects of liquid nitrogen in cryogenic machining has eliminated the production of built up edge effectively, however over-hardening of the workpiece material and the presence of hard silicon particles has resulted in flank wear on the flank surface of the cutting tool. Figure 5 provides a microscopic view of the worn flank face of the titanium coated carbide tool under cryogenic machining. Unlike dry and cryogenic machining, emulsion coolant effectively protected the cutting tool and the cutting edge remained intact after machining. Even though extensive experimentation was not conducted, it is clear to see the benefits of the process from the results initially generated and the authors feel that this represents significant potential long term extrapolated benefits to industry.

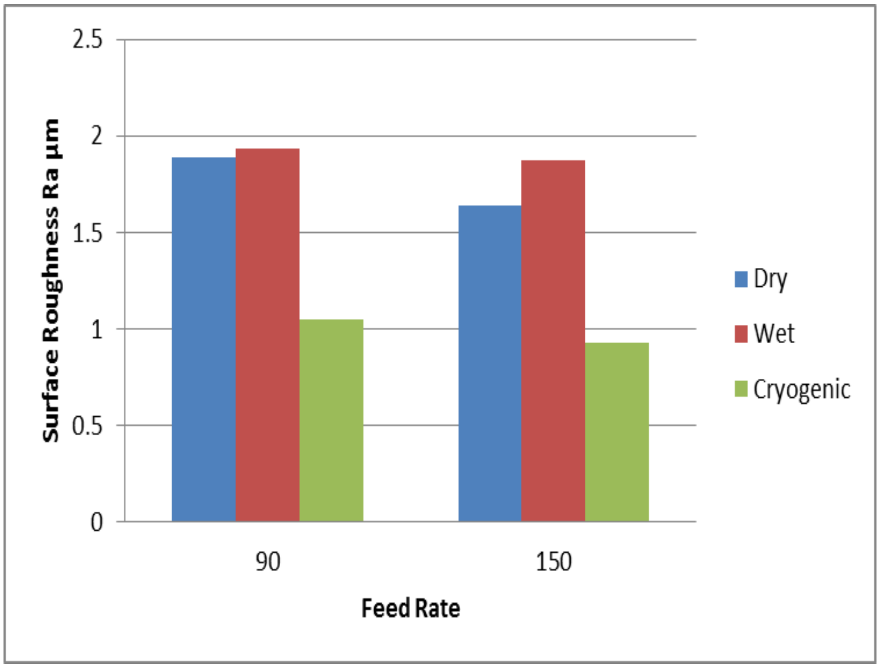

Figure 3 : comparison of the surface roughness of surfaces machined under different environments at S=5000rpm and f=90mm/min

Dry Machining

Cryogenic Machining

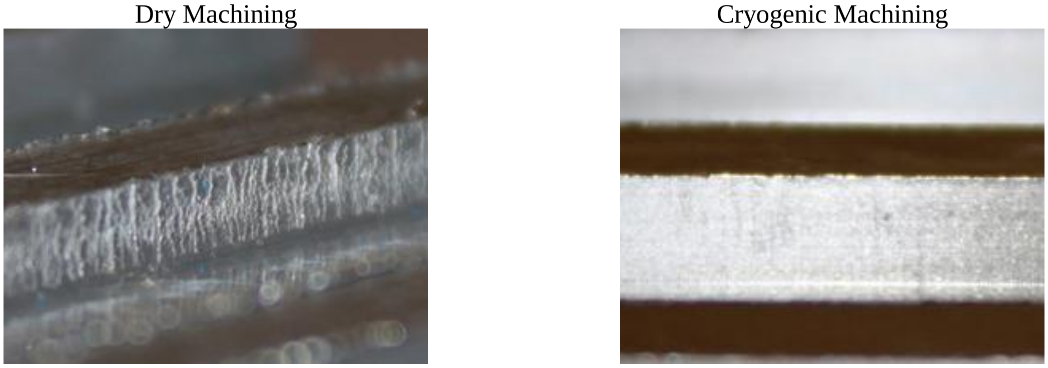

Figure 4 : Surface quality of slots walls produced by dry and cryogenic machining

a) b) c)

Figure 5 : microscopic presentation of worn tools under a) cryogenic; b&c) dry environments
a)Flank wear of the carbide tool under cryogenic environment b) Chipping of the cutting edge in dry machining
c)Built up edge in dry machining

5. CONCLUSIONS

Due to the health and environmental hazards accompanied with conventional oil-based cutting fluids and the extending governmental regulations, the costs associated with the use and disposal of cutting fluids is increasing. There have been many efforts such as dry machining, minimum quantity lubricant (MQL), chilled air and cryogenic machining which have been implemented to reduce or eliminate the use of cutting fluids in material cutting. Studies documented in the literature section suggest that cryogenic cooling has demonstrated promising results towards improving the machinability of difficult-to-machine materials in turning operations. However there are a very limited number of studies on milling and drilling applications. In addition, whilst aluminium is one of the most used structural materials in industries except a study by Biermann and Heilmann [16] there is no significant study on the cryogenic milling of aluminium alloys. In this research the effect of cryogenic cooling on the surface roughness in end-milling of 6061-T6 aluminium has been studied. In addition, the tool wear mode under different cutting environments has been studied.

Experimental investigations revealed that cryogenic cooling is an effective method for helping to eliminate the use of cutting fluids and improve the surface finish of the machined parts. In this study, cryogenic cooling resulted in up to 43% reduction in the surface roughness as compared to dry. Interestingly, the experiments illustrated that using conventional cutting fluids is not favourable when the surface quality is of interest as the highest surface roughness was produced under wet condition as compared to dry and cryogenic machining. As a result, it could be concluded that cryogenic cooling is an effective method to eliminate the use of conventional cutting fluids in machining aluminium alloys whilst increasing the machinability.

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